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The Occurrence of Herbicide-Resistant Weeds Worldwide*

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Abstract: The 1995/6 International Survey of Herbicide-Resistant Weeds recorded 183 herbicide-resistant weed biotypes (124 different species) in 42 countries. The increase in the number of new herbicide-resistant weeds has remained relatively constant since 1978, at an average of nine new cases per year worldwide. Whilst 61 weed species have evolved resistance to triazine herbicides, this figure now only accounts for one-third of all documented herbicide-resistant biotypes. Triazine-resistant weeds have been controlled successfully in many countries by the use of alternative herbicides. Due to the economic importance of ALS and ACCase inhibitor herbicides worldwide, and the ease with which weeds have evolved resistance to them, it is likely that ALS and ACCase inhibitor-resistant weeds will present farmers with greater problems in the next five years than triazine-resistant weeds have caused in the past 25 years. Thirty-three weed species have evolved resistance to ALS-inhibitor herbicides in 11 countries. ALS-inhibitor-resistant weeds are most problematic in cereal, corn/soybean and rice production. Thirteen weed species have evolved resistance to ACCase inhibitors, also in 11 countries. ACCase inhibitor resistance in *Lolium* and *Avena* spp. threatens cereal production in Australia, Canada, Chile, France, South Africa, Spain, the United Kingdom and the USA. Fourteen weed species have evolved resistance to urea herbicides. Isoproturon-resistant *Phalaris minor* infesting wheat fields in North West India and chlorotoluron-resistant *Alopecurus myosuroides* in Europe are of significant economic importance. Although 27 weed species have evolved resistance to bipyridilium herbicides, and 14 weed species have evolved resistance to synthetic auxins, the area infested and the availability of alternative herbicides have kept their impact minimal. The lack of alternative herbicides to control weeds with multiple herbicide resistance, such as *Lolium rigidum* and *Alopecurus myosuroides*, makes these the most challenging resistance problems. The recent discovery of glyphosate-resistant *Lolium rigidum* in Australia is a timely reminder that sound herbicide-resistant management strategies will remain important after the widespread adoption of glyphosate-resistant crops.

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1 INTRODUCTION

In the past 50 years, starting with the introduction of 2,4-D in 1946, agrochemical companies have successfully developed and brought to market a wide array of selective herbicides. Herbicides have revolutionized weed control in the developed world and are rapidly being adopted in developing countries. Why? Herbicides are often the most reliable and least expensive method of weed control available. The success of herbicides and other crop protection chemicals is largely responsible for the abundant and sustained food production necessary to support the current world population. The use of herbicides has simplified weed management in many cropping systems, so it is no longer necessary for farmers to juggle tillage, grazing animals, burning, cover crops, fallow and crop rotations in an attempt to keep weed populations at acceptable levels. Herbicides and other crop-protection chemicals have provided farmers with the tools to grow their most profitable crop, year after year, on the same fields—and for short-term economic reasons this is exactly what many farmers around the world are doing. Reliance upon herbicides as the primary method of weed control in cropping systems is understandable but has some serious drawbacks. The utility of herbicides is being threatened by the appearance of herbicide-resistant weeds. The aim of this paper is to document the current status of herbicide-resistant weeds worldwide.

2 DEFINITIONS

Below are the terms used in this review to describe characteristics of resistant weed biotypes.[1–3]

Resistance is the naturally occurring inheritable ability of some weed biotypes within a population to survive a herbicide treatment that would, under normal conditions of use, effectively control that weed population. Selection of resistant biotypes may eventually result in control failures.

Cross-resistance is where a weed biotype is resistant to two or more herbicides due to the presence of a single resistance mechanism.

Multiple resistance refers to situations where resistant plants possess two or more distinct resistance mechanisms.

3 INTERNATIONAL SURVEY OF HERBICIDE-RESISTANT WEEDS

The purpose of the 'International Survey of Herbicide-Resistant Weeds' is to monitor the occurrence of herbicide-resistant weeds and assess their economic impact throughout the world. In 1995 and 1996, survey forms were sent to 430 weed research and extension people throughout the world in 53 countries and over 300 survey forms have been returned. Survey questions were aimed at identifying the species and herbicide involved, when resistance was first identified, how resistance was confirmed, the crop or vegetation management situation involved, the number of sites and area infested, the location of resistant weeds and the economic impact of resistant weeds. To be included as a 'resistant weed biotype' respondents had to indicate that resistance was identified by research (not just assumed) and that a confirmation test included a side-by-side comparison between a susceptible and resistant population. The preferred method of confirming herbicide-resistant weeds is to conduct whole plant dose-response experiments on resistant and susceptible biotypes of the same species under greenhouse or growth chamber conditions.[4,5]

The last worldwide survey of resistant weeds was conducted by Homer LeBaron and was reported in 1990 and 1991.[6–8] LeBaron is to be commended for initiating worldwide surveys of resistant weeds in the 1970s and has been of great assistance in tracking down many of the resistant weeds reported in the current survey. There are a number of weed species and locations reported in LeBaron's last survey that are not, as yet, included in the current survey. There are also discrepancies (between surveys) in the year recorded for the first case of resistance. Most of these differences relate to triazine-resistant weeds and nearly all of the discrepancies exist because of the stipulation in the current survey that side-by-side confirmation tests must have been completed. This survey is on-going and continually improved by suggestions from weed scientists. Due to the nature of surveys there will always be errors and omissions. If the reader can improve the quality of data in the survey or knows of new cases of resistant weeds, please contact the author. For a current list of herbicide-resistant weeds please refer to the 'International Survey of Herbicide-Resistant Weeds' web site at http://www.pioneer.net/ ~ heapian/, or contact the author for a booklet containing a current list of herbicide-resistant weeds.

4 CONFIRMED CASES OF HERBICIDE RESISTANCE WORLDWIDE

4.1 Chronology of resistance

The 1995/6 International Survey of Herbicide-Resistant Weeds recorded 183 herbicide-resistant weed biotypes in 42 countries (Tables 1 and 2). A new resistant biotype refers to the first instance of a weed species evolving resistance to one or more herbicides in a herbicide group. For instance, the occurrence of triazine-resistant *Amaranthus retroflexus* L. in 10 countries is recorded as one resistant biotype, while the occurrence of ALS-

TABLE 1
Occurrence of Resistant Weed Biotypes to Different Herbicide Groups

Herbicide group	*WSSA[a] code*	*HRAC[b] code*	*Example*	*Resistant weed biotypes*			*Number of countries[c]*
				Dicots	*Monocots*	*Total*	
Triazines	5	C1	Atrazine	43	18	61	20
ALS inhibitors	2	B	Chlorsulfuron	26	7	33	11
Bipyridiliums	22	D	Paraquat	20	7	27	12
Ureas/amides	7	C2	Chlorotoluron	5	11	16	13
Synthetic auxins	4	O	2,4-D	12	2	14	11
ACCase inhibitors	1	A	Diclofop-methyl	0	13	13	11
Dinitroanilines	3	K1	Trifluralin	1	5	6	4
Triazoles	11	F3	Amitrole	1	3	4	2
Chloroacetamides	15	K3	Metalochlor	0	2	2	2
Thiocarbamates	8	N	Triallate	0	2	2	3
Nitriles	6	C3	Bromoxynil	1	0	1	1
Glycines	9	G	Glyphosate	0	1	1	1
PPO inhibitors	14	E	Oxyfluorfen	0	1	1	1
Benzofurans	16	N	Ethofumesate	0	1	1	1
Organoarsenicals	17	Z	MSMA	1	0	1	1
			Totals	110	73	183	

[a] Weed Science Society of America herbicide classification. Available from James Retzinger, American Cyanamid Company, 4101 Vividell Circle, West Des Moines, IA 50266 USA.
[b] Herbicide Resistance Action Committee herbicide classification. Avalable from HRAC Publicity Office c/o David Nevill & Derek Cornes, Ciba Crop Protection Division, 4002 Basel Switzerland.
[c] A country may be counted in more than one herbicide group, thus this column adds up to more than the 42 listed in Table 2.

inhibitor-resistant *A. retroflexus* in three countries is recorded as a second resistant biotype. There are 124 weed species that have evolved resistance to one or more herbicides. Of the resistant biotypes, 32% are triazine-resistant, 18% are resistant to ALS inhibitor herbicides, 15% to bipyridiliums, 9% to phenylureas/amides, 8% to synthetic auxins, 7% to ACCase inhibitors, 3% to dinitroanilines and the remaining 8% are resistant to other herbicide modes of action (Table 1). Not surprisingly, most herbicide-resistant weed biotypes have evolved in developed countries where herbicides are the primary weed control method (Table 2). Forty-nine resistant weed biotypes are found in the USA, 24 in France and Spain, 22 in Australia and Canada, 18 in Israel and 16 in the United Kingdom (Table 2). Figure 1 indicates the chronological rate of increase in the number of new resistant weed biotypes. There were relatively few reports of herbicide-resistant weeds prior to the often-cited discovery of triazine-resistant common groundsel (*Senecio vulgaris* L.) in 1968.[9] In the period between 1970 and 1977 an average of one new herbicide-resistant weed biotype was discovered per year. In the late 1970s many scientists became interested in the phenomenon of triazine resistance and the rate of identification of new cases of resistant weeds increased. Since 1978 the number of new cases of herbicide-resistant weed biotypes has been relatively constant, averaging nine new cases per year (Fig. 1). Initially

TABLE 2
Number of Resistant Weed Biotypes in each of 42 Countries

Country	*No.*	*Country*	*No.*	*Country*	*No.*	*Country*	*No.*
USA	49	Malaysia	9	South Africa	3	Fiji	1
France	24	Japan	8	Austria	2	Greece	1
Spain	24	Poland	8	Egypt	2	Hungary	1
Australia	22	Chile	6	Indonesia	2	India	1
Canada	22	New Zealand	5	Kenya	2	Philippines	1
Israel	18	The Netherlands	5	Mexico	2	Portugal	1
United Kingdom	16	China	4	Norway	2	Slovenia	1
Germany	15	Costa Rica	4	Brazil	1	Sweden	1
Switzerland	13	Korea	4	Colombia	1	Taiwan	1
Belgium	11	Bulgaria	3	Denmark	1		
Czech Republic	9	Italy	3	Ecuador	1		

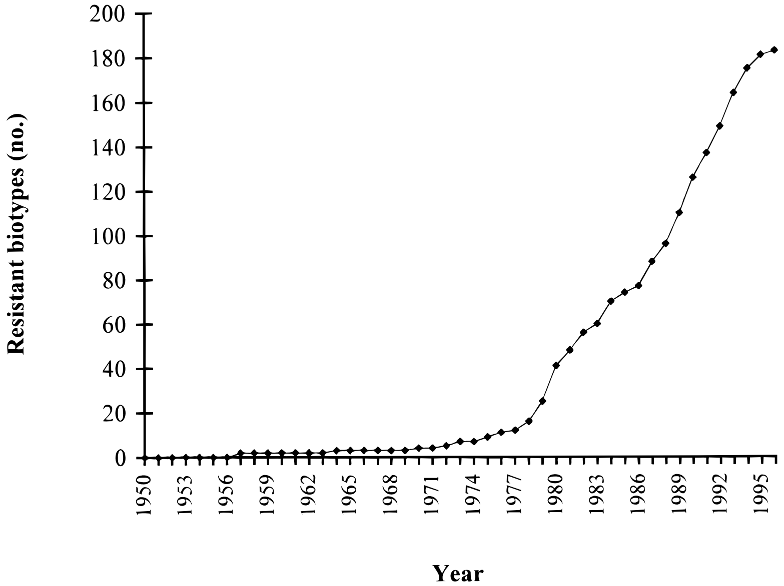

Fig. 1. The chronological increase in the number of herbicide-resistant weeds worldwide.

triazine-resistant weeds accounted for much of this nine-fold increase in the rate of documentation of herbicide resistance. In the five-year period between 1978 and 1983, scientists around the world documented 33 new cases of triazine-resistant weeds (Fig. 2). The predominance of triazine-resistant weeds was largely due to the effectiveness and the widespread use of atrazine for weed control in maize, and of simazine for weed control in orchards. By 1983, triazine-resistant weeds accounted for 67% of the documented cases of herbicide resistance. Weeds resistant to the bipyridiliums accounted for 13%, synthetic auxins 12% and all other herbicide modes of action 8%. These proportions changed as weeds began evolving resistance to herbicides with new modes of action that were brought to market in the late 1970s and early 1980s. In the period between 1984 and 1997 triazine-resistant weeds accounted for only 16% of the newly reported cases of herbicide resistance. In this same period, weeds resistant to ALS-inhibitor herbicides accounted for 27%, bipyridiliums 15%, phenylureas/amides 12%, ACCase inhibitors 9%, synthetic auxins 6%, dinitroanilines 4% and all other modes of action 11% of reported cases (Fig. 2).

4.2 Triazines

There are currently 43 dicotyledonous and 18 monocotyledonous weed species that have evolved resistance to triazine herbicides (Table 1). The majority of triazine-

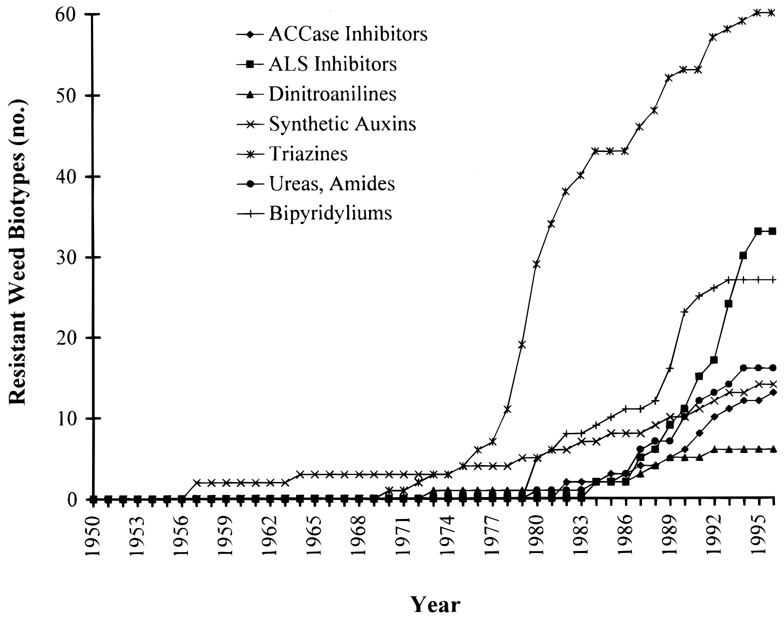

Fig. 2. The chronological increase in the number of herbicide-resistant weeds for several herbicide classes.

resistant weeds were identified in maize production in North America and Europe or in orchards in Europe. Triazine-resistant weeds have been reported in nine *Amaranthus* species, five *Polygonum* species and four *Chenopodium* species. The most frequently reported triazine-resistant weeds are *Chenopodium album* L. (16 countries), *A. retroflexus* (10 countries), *S. vulgaris* (10 countries) and *Solanum nigrum* L. (nine countries). It is estimated that there are over three million hectares infested with triazine-resistant weeds worldwide, making them the most widespread resistance problem. Triazine-resistant weeds have been controlled successfully in many countries by the use of alternative herbicides.

4.3 ALS inhibitors

Herbicides that inhibit acetolactate synthase (ALS inhibitors) accounted for 17% of global herbicide sales in 1994, more than any other single herbicide group.[10] ALS inhibitors have been widely used because of their low use rates, high efficacy, low mammalian toxicity and good selectivity in over 12 major crops.[11] A combination of this widespread usage and the ease with which weeds evolve resistance to ALS-inhibitor herbicides has resulted in the selection of 33 ALS-inhibitor-resistant weed species (26 dicotyledon and seven monocotyledon species) in a total of 11 countries (Table 1). There are 13 ALS-inhibitor-resistant weed species found in the USA, nine in Australia, five in Canada and five in Israel (Table 3). New cases of ALS-inhibitor-resistant weeds have increased at a greater annual rate than any other herbicide mode of action over the last 10 years (Fig. 2). ALS-inhibitor-resistant weeds have appeared in cereals, corn/soybean rotations, rice, highway rights-of-way and forestry. ALS-inhibitor-resistant *Kochia scoparia* Roth and *Salsola iberica* Sennen & Pau have become widespread problems in cereal-producing regions of North Western United States and Canada. The mobility of these tumbleweeds has undoubtedly contributed to the rate of spread of resistance. Several *Amaranthus* species, *Xanthium strumarium* L. and *Sorghum bicolor* Moench have evolved resistance to ALS inhibitor herbicides in the Mid-West corn/soybean belt. The use of bensulfuron for weed control in rice has led to the selection of ALS-inhibitor-resistant *Alisma plantago-aquatica* L. in Portugal, *Damasonium minus* in Australia and *Sagittaria montevidensis* and *Cyperus difformis* L. in both the USA and Australia (Table 3).

4.4 Bipyridiliums

The bipyridiliums paraquat and diquat are non-persistent, non-selective, fast-acting post-emergence herbicides that have been used widely throughout the world for weed control especially in orchards and plantations. In 1980, paraquat-resistant *Conyza canadensis*, *Erigeron philadelphicus* L., *E. sumatrensis* and *Youngia japonica* DC. were identified in orchards in Japan. Twenty-five weed species have evolved resistance in response to paraquat applications, and two weed species (*Arctotheca calendula* Levyns and *Conyza linifolia*) have evolved resistance in response to diquat. In total there are 20 dicotyledon species and seven monocotyledon species with resistance to bipyridyl herbicides (Table 1). Due to the limited acreage infested with bipyridilium-resistant weeds, and the effectiveness of alternative herbicides, these resistant biotypes have not had a severe economic impact.

4.5 Phenylureas and phenylamides

Fourteen weed species have evolved resistance to the phenylureas and two have evolved resistance to propanil (an amide). The first phenylurea-resistant weed to appear was *Alopecurus myosuroides* Huds. from the United Kingdom (1982) and Germany (1983), originally selected through chlorotoluron usage in cereals. These chlorotoluron-resistant *A. myosuroides* populations present severe control problems because they have the ability to metabolize a wide range of herbicides with different modes of action.[12] Several phenylurea-resistant weeds have the potential to seriously affect food production in the developing world. Of particular concern are populations of chlorotoluron-resistant *Alopecurus japoniens* identified in wheat fields in China in 1991, and the widespread occurrence of isoproturon-resistant *Phalaris minor* Retz in India, also identified in wheat fields in 1991.[13] Propanil is used throughout the world for weed control in rice, and several hundred populations of propanil-resistant *Echinochloa crus-galli* Beauv. and *Echinochloa colona* Link have been identified in Columbia, Costa Rica, Greece and the USA.

4.6 Synthetic auxins

The synthetic auxins 2,4-D and MCPA revolutionized broadleaved weed control in cereals in the late 1940s and have been used extensively throughout the world ever since. Considering the extensive use of synthetic auxins for over 50 years, relatively few weeds have evolved resistance. Resistance to 2,4-D was first identified in two species in 1957,[14,15] although this work is rarely cited because of the low level of resistance exhibited in comparison to the triazine-resistant common groundsel reported by Ryan in 1970.[9] Hilton[14] had identified populations of spreading dayflower (*Commelina diffusa* Burm.) resistant to 2,4-D in Hawaiian sugar cane fields in 1957.[14] One population of spreading dayflower was over five times more resistant to 2,4-D than a susceptible population. In the same year Canadian researchers reported populations of wild

TABLE 3
Occurrence and Distribution of ALS-Inhibitor-Resistant Weeds Worldwide. WSSA Group 2. HRAC Group B

Species	*Common name*[a]	*Selective agent*[b]	*Country and year first identified*
Dicotyledons			
Alisma plantago–aquatica	Common Waterplantain	Bensulfuron	Portugal (1995)
Amaranthus blitoides	Prostrate Pigweed	Sulfonylureas	Israel (1991)
Amaranthus hybridus	Smooth Pigweed	Imazaquin	USA (1994)
Amaranthus palmeri	Palmer Amaranth	Imazethapyr	USA (1991)
Amaranthus retroflexus	Redroot Pigweed	Sulfonylureas	Israel (1991); USA (1995)
Amaranthus rudis	Common Waterhemp	Imazethapyr	USA (1993)
Bidens pilosa	Hairy Beggarticks	Imazaquin	Brazil (1993)
Brassica tournefortii	Wild Turnip	Chlorsulfuron	Australia (1992)
Conyza bonariensis	Hairy Fleabane	Sulfonylureas	Israel (1993)
Conyza canadensis	Horseweed	Sulfonylureas	Israel (1993)
Cuscuta campestris	Field Dodder	Sulfonylureas	Israel (1994)
Damasonium minus	Starfruit	Bensulfuron	Australia (1994)
Fallopia convolvulus	Climbing Buckwheat	Chlorsulfuron	Australia (1993)
Galeopsis tetrahit	Common Hempnettle	ALS inhibitors	Canada (1995)
Ixophorus unisetum	Pasto Honduras	Imazapyr	Costa Rica (1988)
Kochia scoparia	Kochia	Chlorsulfuron	USA (1987); Canada (1988)
Lactuca serriola	Prickly Lettuce	Chlorsulfuron	USA (1987); Australia (1994)
Monochoria korsakoii		Sulfonylureas	Japan (1994)
Sagittaria montevidensis	Arrowhead	Bensulfuron	USA (1993); Australia (1994)
Salsola iberica	Russian Thistle	Chlorsulfuron	USA (1987)
Sida spinosa	Prickly Sida	Imazaquin	USA (1995)
Sinapis arvensis	Wild Mustard	Chlorsulfuron	Canada (1992)
Sisymbrium orientale	Indian Hedge Mustard	Triasulfuron	Australia (1990)
Sonchus oleraceus	Sowthistle	Chlorsulfuron	Australia (1990)
Stellaria media	Common Chickweed	Chlorsulfuron	Denmark (1991); Canada (1992); New Zealand (1995)
Xanthium strumarium	Common Cocklebur	Imidazolinones	USA (1989)
Monocotyledons			
Alopecurus myosuroides	Black-grass	Sulfonylureas	United Kingdom (1984)
Avena fatua	Wild Oat	Imazamethabenz	Canada (1994)
Eleusine indica	Goosegrass	Imazapyr	Costa Rica (1989)
Lolium perenne	Perennial Ryegrass	Sulfometuron	USA (1989)
Lolium rigidum	Rigid Ryegrass	Sulfonylureas	Australia (1984)
Sorghum bicolor	Shattercane	ALS inhibitors	USA (1994)
Sedges			
Cyperus difformis	Dirty Dora	Bensulfuron	USA (1993); Australia (1994)

[a] From 'The WSSA Composite List of Weeds', revised 1989. Available from WSSA, 1508 West University Ave, Champaign, IL 61821-3133.
[b] This refers to the primary selective agent in the first reported case of resistance.

carrot (*Daucus carota* L.) that had evolved 2,4-D resistance on sections of highway rights-of-way regularly treated with 2,4-D.[15,16] The widespread use of 2,4-D and MCPA in wheat has led to synthetic-auxin-resistant *Papaver rhoeas* L. in Spain, *Sinapis arvensis* L. in Canada and *Matricari perforata* Merat in France. In NewZealand pastures *Cardus nutans* L. and *Ranunculus acris* L. have evolved resistance to 2,4-D and MCPA. 2,4-D has also been used extensively in rice production, resulting in the selection of 2,4-D-resistant *Limnocharis flava* Buchen. in Indonesia, *Sphenoclea zeylanica* Gaertn. in the Philippines and Malaysia and *Fimbristylis miliacea* Vahl also in Malaysia. Few of the synthetic-auxin-resistant weeds have had a significant economic impact due to the wide array of alternatives that successfully control these resistant weeds. In total 14 weed species have evolved resistance to synthetic auxin herbicides (Table 1).

4.7 ACCAse inhibitors

Herbicides that inhibit the enzyme Acetyl-Coenzyme A Carboxylase (ACCase inhibitors) were first introduced in the late 1970s. ACCase inhibitors provide excellent grass-weed control in both cereal and dicotyledonous crops. They have gained widespread acceptance in the

market and now account for more than 5% of global herbicide sales.[10] Thirteen grasses have evolved resistance to ACCase inhibitors (Table 4). The extensive use of diclofop-methyl for grass control in wheat worldwide led to the first occurrences of ACCase-inhibitor-resistant weeds. *Lolium* spp. have evolved resistance to diclofop-methyl and other ACCase inhibitors in Australia, Chile, France, South Africa, Spain, the United Kingdom and the USA (Table 4). Similarly, *Avena* spp. have evolved resistance to ACCase inhibitors in Australia, Canada, Chile, South Africa, the United Kingdom and the USA. It is estimated that there are more than 3000 ACCase-inhibitor-resistant *Lolium rigidum* Gaud. sites in Australia, and more than 500 ACCase-inhibitor-resistant *Avena fatua* L. sites in Canada and North Western USA. Also of considerable economic importance are ACCase-inhibitor-resistant *Phalaris* spp. from Mexico and *Setaria* spp. in North America (Table 4). ACCase-inhibitor-resistant grasses are of major economic importance globally because of the number of acres infested and the limited number of alternative herbicide modes of action available for their control.

4.8 Dinitroanilines

Dinitroaniline herbicides, such as trifluralin, ethalfluralin, oryzalin and pendimethalin, have been used for pre-emergence weed control over the last 25 years in cotton, soybean, wheat and oilseed crops. Despite their long persistence and extensive use, only five monocotyledonous and one dicotyledonous plants have evolved resistance to dinitroaniline herbicides (Table 1). Cross-resistance (*via* enhanced metabolism) accounts for two of the dinitroaniline-resistant monocotyledons, *L. rigidum*[17] and *A. myosuroides*.[12] In the cotton-producing areas of the Southeastern USA dinitroaniline-resistant *Eleusine indica* (L) Gaertn., *Sorghum halepense* (L) Pers. and *Amaranthus palmeri* S. Wats. had evolved after 10 to 15 applications of trifluralin. Dinitroaniline-resistant *E. Indica* is the most widespread of these problem weeds, and now infests over 1000 cotton fields in North and South Carolina, Alabama, Georgia and Tennessee. Dinitroaniline-resistant populations of *Setaria viridis* Beauv. have evolved after 15 to 20 years of use of trifluralin in cereals and oilseed crops on the Canadian prairies and in North Dakota, USA. ACCase-inhibitor herbicides are the primary alternative mode of action for control of dinitroaniline-resistant *S. viridis*, which has led to the selection of multiple resistance in this species.[18]

4.9 Glyphosate

Glyphosate is considered a low risk herbicide for the evolution of herbicide resistance.[19] Its mode of action, chemical structure, limited metabolism in plants, use pattern and lack of residual activity are often cited as reasons why this herbicide is unlikely to select for resistance.[19] Like glyphosate, paraquat is also non-residual and has been used in orchards and as a pre-plant knockdown herbicide, yet 27 weed species have evolved resistance to paraquat (Table 1). The most convincing argument that glyphosate is a 'low risk for resistance' herbicide is that, despite a long history of extensive use, only one weed, *Lolium rigidum*, has evolved glyphosate

TABLE 4
Occurrence and Distribution of ACCase-Inhibitor-Resistant Weeds Worldwide. WSSA Group 1. HRAC Group A

Species	*Common name*[a]	*Selective agent*[b]	*Country and year first identified*
Alopecurus myosuroides	Black-grass	Chlorotoluron	United Kingdom (1982); Germany (1983); France (1993)
Avena fatua	Wild Oat	Diclofop	Australia (1985); South Africa (1986); Canada (1990); USA (1990); Chile (1995)
Avena sterilis	Wild Oat	Diclofop	Australia (1989); United Kingdom (1993)
Digitaria sanguinalis	Large Crabgrass	Fluazifop	USA (1992); Australia (1993)
Echinochloa colona	Junglerice	Fenoxaprop	Costa Rica (1994)
Eleusine indica	Goosegrass	Fluazifop	Malaysia (1990)
Lolium multiflorum	Italian Ryegrass	Diclofop	USA (1987); United Kingdom (1990); South Africa (1993)
Lolium rigidum	Rigid Ryegrass	Diclofop	Australia (1982); Spain (1992); Chile (1995).
Phalaris minor	Little Seed Canary Grass	Fenoxaprop	Israel (1993); Mexico (1996)
Phalaris paradoxa	Hooded Canary Grass	Fenoxaprop	Mexico (1996)
Setaria faberi	Giant Foxtail	Fluazifop	USA (1991)
Setaria viridis	Green Foxtail	Diclofop	Canada (1992)
Sorghum halepense	Johnsongrass	Fluazifop	USA (1991)

[a] From 'The WSSA Composite List of Weeds' revised 1989. Available from WSSA, 1508 West University Ave, Champaign, IL 61821-3133.
[b] This refers to the primary selective agent in the first reported case of resistance.

resistance. In 1996 glyphosate-resistant rigid ryegrass (*L. rigidum*) was identified near the town of Echuca in Northern Victoria, Australia (J. Pratley, pers. commun). Since 1987 the farmer had grown sunflowers, wheat, chickpeas, faba beans, tomatoes, dill, safflower and had sometimes fallowed on this 20-ha field. Glyphosate had been used on the field for pre-plant weed control at least 10 times in the previous 15 years, resulting in the selection of glyphosate-resistant rigid ryegrass. In confirmation studies (three replicated dose-response experiments over a wide range of glyphosate rates) the resistant population was at least six times more resistant to glyphosate than a normal susceptible population. The appearance of glyphosate-resistant rigid ryegrass should be a forewarning. The recently developed glyphosate-resistant crops will need to be used in rotation with conventional cultivars, and in conjunction with non-chemical weed control and other herbicides if the selection of glyphosate-resistant weeds is to be avoided.

4.10 Other herbicide modes of action

Chloracetamide-resistant weeds have not been reported from maize fields, despite the widespread and continuous use of herbicides such as metalochlor and alachlor in maize production. In 1993, however, chloracetamide resistance in *E. crus-galli* appeared in rice fields in China. These populations are found in most provinces in south China and have been selected with either butachlor and/or thiobencarb. At least some of the populations are known to be resistant to both herbicides. Four weed species have evolved resistance to the herbicide amitrole. In Belgium *Agrostis stolonifera*, *Poa annua* L. and *Polygonum aviculare* L. have evolved amitrole resistance after repeated amitrole applications in orchards. Amitrole-resistant *L. rigidum* has also been identified on railway lines in Australia. MSMA/DSMA-resistant populations of *X. strumarium* had evolved in cotton fields in the USA by 1985 and are now found in five southern states. In 1994 over 20 populations of ethofumesate-resistant *P. annua* were found in grass seed fields in Oregon. These *P. annua* populations are also resistant to triazines and urea herbicides. In 1995 several populations of bromoxynil-resistant *S. vulgaris* were identified in mint fields, also in Oregon. In Alberta, Canada and Montana, USA, over 300 cereal producers have selected triallate-resistant wild oat. These populations present an added difficulty in that they are also resistant to difenzoquat.

4.11 Multiple resistance and enhanced metabolism of herbicides

Herbicide-resistant weeds have the greatest economic impact on crop production when there are few or no alternative herbicides to control resistant biotypes. Weeds that have multiple resistance are therefore of great concern to farmers. These usually result from the use of two or more herbicides with modes of action selecting for two or more distinct resistance mechanisms. For instance, once Canadian farmers had selected populations of dinitroaniline-resistant *Setaria viridis* they switched to ACCase-inhibitor products which resulted in the selection of *S. viridis* populations that are resistant to herbicides in both groups.[18] *Poa annua* resistant to atrazine, diuron, terbacil and ethofumesate in Oregon,[20] *A. fatua* resistant to fenoxaprop, imazamethabenz and flamprop-methyl in Canada, *A. fatua* resistant to diclofop-methyl and pronamide in Oregon and *E. crus-galli* resistant to butachlor and thiobencarb in China may have evolved due to multiple resistance mechanisms or enhanced metabolism. A few broadleaf species have also evolved multiple resistance, the most notable being *Kochia scoparia* from the USA and *Amaranthus blitoides* S. Wats. from Israel with triazine and ALS-inhibitor resistance. The ability to resist numerous unrelated herbicide chemistries as a result of enhanced herbicide metabolism is the least predictable and most challenging resistance problem. The broad spectrum of herbicide resistance identified in *L. rigidum* from Australia[17,21,22] and *A. myosuroides* from Europe[23,24] have made these resistant weeds very difficult to control.

5 CONCLUSIONS

Weeds evolve resistance to herbicides at different rates.[25] The differences are due to the extent of commercial use (number of years and area applied per year) of a herbicide, and the relative ease (risk factor) with which weeds evolve resistance to the herbicide. Both triazine and synthetic auxin herbicides have been used on millions of acres of maize or cereals for over 30 years, often without rotation. Yet there are 61 species that have evolved triazine resistance and only 14 that have evolved synthetic auxin resistance. Clearly there is a greater risk of selecting resistant weeds with triazines than with synthetic auxins (Fig. 2). Few weeds have evolved resistance to chloracetamides, diphenylethers and glyphosate, despite extensive use of these herbicides; therefore they are considered a low risk for the selection of herbicide-resistant weeds. Weeds have readily evolved resistance to triazines, ALS inhibitors, bipyridyliums, phenylureas and ACCase inhibitors. In the last 10 years more weeds have been identified with ALS-inhibitor resistance than for any other herbicide mode of action. The initial high frequency of ALS-inhibitor-resistant individuals in weed populations prior to herbicide use, the persistence of many ALS-inhibiting herbicides and the large number of acres treated repeatedly with ALS-inhibitor herbicides worldwide contrib-

ute to this rapid increase in ALS-inhibitor-resistant weeds. It is notable that few weeds have evolved resistance to ALS-inhibitor herbicides in Europe where ALS-inhibitor herbicides are used in rotation with other herbicides. In the last 50 years herbicides have simplified weed management for many farmers. As farmers struggle with herbicide-resistant weed populations, many weed scientists call for a return to long-term complex weed-control strategies utilizing tillage, grazing animals, burning, cover crops, fallow and crop rotations in conjunction with herbicides. The environmental and economic problems associated with returning to tillage, burning and fallow for weed control make these recommendations unpopular with farmers. Many farmers will gamble on herbicide rotation (assisted by new herbicide-resistant crops)[26] and the rate of discovery of new compounds to keep one step ahead of troublesome herbicide-resistant weeds. The evidence of broad-spectrum multiple resistance in grass-weeds makes this a risky gamble.

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REFERENCES

1. Rubin, B., Herbicide resistance in weeds and crops; progress and prospects. In *Herbicide Resistance in Weeds and Crops*, ed. J. C. Caseley, G. W. Cussans & R. K. Atkin. Butterworth-Heinemann, Oxford, 1991, pp. 387–414.
2. O'Keeffe, M. G., Graham J. C. & Jutsam, A. R., Herbicide Resistant Action Committee 1993. *Pestic. Outlook*, **4** (1993) 15–19.
3. Jutsum, A. R. & Graham J. C., Managing weed resistance: The role of the agrochemical industry. *Proc. Brighton Crop Prot. Conf.—Weeds*, 1995, pp. 557–66.
4. Heap, I. M., Identification and documentation of herbicide resistance. *Phytoprotection*, **75** (1994) 85–90.
5. Moss, S. R., Techniques for determination of herbicide resistance. *Proc. Brighton Crop Prot. Conf.—Weeds*, 1995, pp. 547–56.
6. Holt, J. S. & LeBaron, H. M., Significance and distribution of herbicide resistance. *Weed Tech.*, **4** (1990) 141–9.
7. LeBaron, H, M., Herbicide resistance in crops and weeds and its management. *Proc. 3rd Tropical Weed Sci. Conf. Kuala Lumpur, Malaysia*, ed. S. A. Lee & K. F. Ko, 1991, pp. 61–70.
8. LeBaron, H. M., Distribution and seriousness of herbicide-resistant weed infestations worldwide. In *Herbicide Resistance in Weeds and Crops*, ed. J. C. Caseley, G. W. Cussans & R. K. Atkin. Butterworth-Heinemann, Oxford, 1991, pp. 27–43.
9. Ryan, G. F., Resistance of common groundsel to simazine and atrazine. *Weed Sci.*, **18** (1970) 614–16.
10. Wood Mackenzie, Agrochemical Service. Kintore House, 74–77 Queen Street, Edinburgh EH2 4NS, Scotland, UK: Crop Pesticide Sectors, May 1995.
11. Brown, H. M. & Cotterman, J. C., Recent advances in sulfonylurea herbicides. In *Chemistry of Plant Protection*, Springer-Verlag, Berlin & Heidelberg, **10** (1994) 49–81.
12. Moss, S. R. & Cussans, G. W., The development of herbicide-resistant populations of *Alopecurus myosuroides* (Black-Grass) in England. In *Herbicide Resistance in Weeds and Crops*, ed. J. C. Caseley, G. W. Cussans & R. K. Atkin. Butterworth-Heinemann, Oxford, 1991, Jpp. 45–55.
13. Malik, R. K. & Singh, S., Littleseed canarygrass (*Phalaris minor*) resistance to isoproturon in India. *Weed Tech.*, **9** (1995) 419–25.
14. Hilton, H. W., Herbicide tolerant strains of weeds. *Hawaiian Sugar Plant. Assoc. Ann. Rep.* (1957) p. 69.
15. Switzer, C. M., The existence of 2,4-D resistant strains of wild carrot. *Proc. North Eastern Weed Control Conf.*, **11** (1957) 315–18.
16. Whitehead, C. W. & Switzer, C. M., The differential response of strains of wild carrot to 2,4-D and related herbicides. *Canad. J. Plant Sci.*, **43** (1963) 255–62.
17. Heap, I. M., Resistance to herbicides in annual ryegrass (*Lolium rigidum*) in Australia. In *Herbicide Resistance in Weeds and Crops*, ed. J. C. Caseley, G. W. Cussans & R. K. Atkin. Butterworth-Heinemann, Oxford, 1991, pp. 57–66.
18. Heap, I. M., Multiple resistance to dinitroaniline and ACCase inhibiting herbicides in green foxtail (*Setaria viridis* (L.) Beauv.). *WSSA abstracts*, St. Louis, Missouri, **56** (1994) 168.
19. Padgette, S. R., Delannay X., Bradshaw L., Wells B. & Kishore G., Development of glyphosate-tolerant crops and perspectives on the potential for weed resistance to glyphosate. In *Internat. Symp. Weed and Crop Resistance to Herbicides*, Cordoba, Spain, 1995, Abstract 92.
20. Heap, I. M., Multiple herbicide resistance in annual bluegrass (*Poa annua*). *WSSA* Abstracts, Seattle, Washington, **42** (1995) 56.
21. Heap, I. M. & Knight R., Variation in herbicide cross-resistance among populations of annual ryegrass (*Lolium rigidum*) resistant to diclofop-methyl. *Aust. J. Agric. Res.*, **41** (1990) 121–8.
22. Heap, I. M. & Knight R., The occurrence of herbicide cross-resistance in a population of annual ryegrass, *Lolium rigidum*, resistant to diclofop-methyl. *Aust. J. Agric. Res.*, **37** (1986) 149–56.
23. Moss, S. R., Herbicide cross-resistance in slender foxtail (*Alopecurus myosuroides*). *Weed Sci.*, **38** (1990) 492–6.
24. Mendenez, J., De Prado, R., Jorrin, J. & Taberner, A., Penetration, translocation and metabolism of diclofop-methyl in chlorotoluron-resistant and susceptible biotypes of *Alopecurus myosuroides*. In *Proc. Brit. Crop Prot. Conf.—Weeds*, 1993, pp. 213–20.
25. Gressel, J. & Segel L. A., Modelling the effectiveness of herbicide rotations and mixtures as strategies to delay or preclude resistance. *Weed Tech.*, **4** (1990) 186–98.
26. Shaner, D. L., Herbicide-resistant crops: A new tool in herbicide-resistant weed management. *Second Intern. Weed Cont. Cong., Copenhagen, Internat. Weed Science Society*, 1996, pp. 421–5.
27. Schmidt, R. R. HRAC classification of herbicides according to mode of action. *Proc. Brighton Crop Prot. Conf.—Weeds* (1997) in press.